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Development of a predictive model for piezoelectric crystal pressure transducer for fluid flow in a pipe system

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Research work was conducted to examine the characteristics of piezoelectric crystal pressure transducer for fluid in a pipe system. Mathematical model was developed in this case to monitor, predict and simulate the effect of time on pressure system, density of the system, velocity of the system and voltage of the system using Matlab computer language programme. Results obtained revealed decrease in voltage with increase in time, using the mathematical techniques of $DE = RCK\ {}^{u}/_{t}$. Increase in velocity was observed with increase in voltage using the mathematical expression of $U = {}^{tDE}/_{Rck}$. Decrease in density was observed with increase in pipe flow length using the mathematical approach of $P = {}^{Pdt}/_{Ldu}$ as well as decrease in pressure within time using the model of $P = k(u - u_o)/t$. The research work demonstrate the usefulness of the various models developed in this paper for monitoring, predicting and simulating the piezoelectric crystal characteristics of pressure transducer for fluid process flow in a pipe system.

INTRODUCTION

A piezoelectric sensor is a device that uses the piezoelectric effect, to measure changes in pressure, acceleration, temperature, strain, or force by converting them to an electrical charge. It is also the ability of certain materials to generate electrical charge due to mechanical deformation. The name comes from an ancient Greek word *piezein* meaning to 'squeeze' or 'press'. It was first discovered in 1880 by the brothers Pierre and Jacques Curie, who demonstrated piezoelectricity in various crystals including zincblende, tourmaline, cane sugar, topaz, and quartz. Within a year, a converse piezoelectric effect was predicted by Lippmann based on thermodynamic considerations of which the behaviour was also confirmed by the Curies (Damsanovic, 1978, Macda, et al., 2004., Ukpaka, 2005).

The first practical applications came a few decades later. In 1918, Langevin developed an ultrasonic submarine detection technique using a quartz-based piezoelectric transducer. This approach, known as sonar, was subsequently used during both world wars. It is also generally accepted that the use of quartz for stabilization of oscillators in the 1920s initiated the field of frequency control (Li et al., 2013, Amadi and Ukpaka, 2007).

Further developments in piezoelectricity took place in the 1950s and 1960s when studies focused on polymers and their properties. In 1969, Kawai discovered strong piezoelectric properties in polyvinylidene fluoride. This breakthrough resulted in huge wave of interest in research and applications of this material. Since then; this measuring principle has been increasingly used, and has become a mature technology with excellent inherent reliability (Ukpaka, 2007).

The main principle of a piezoelectric transducer is that a force, when applied on the quartz crystal, produces electric charges on the crystal surface (Ukpaka, 2005a). The charge thus produced can be referred to as piezoelectricity. Piezoelectricity can be defined as the electrical polarization produced by mechanical strain on certain class of crystals. The rate of charge produced will be proportional to the rate of change of force applied as input. As the charge produced is very small, a charge amplifier is needed so as to produce an output voltage big enough to be measured. The device is also known to be mechanically stiff. For example, if a force of 15KN is given to the transducer, it may only deflect to a maximum of 0.002mm. But the output response may be as high as 100KiloHz and this proves that the device is best applicable for dynamic measurement (Duan et al., 2001).

Figure 1 shows a conventional piezoelectric transducer with a piezoelectric crystal inserted between a solid base and the force summing member. If a force is applied on the pressure port, the same force will fall on the force summing member. Thus a potential difference will be generated on the crystal due to its property. The voltage produced will be proportional to the magnitude of the applied force. Piezoelectric transducer can measure pressure in the same way a force or acceleration can be measured. For low pressure measurement, possible vibration of the amount should be compensated for. The pressure measuring quartz disc stack faces the pressure through a diaphragm and on the other side of this stack, the compensating mass followed by compensating quartz (Hyan, et al., 2013). The way a piezoelectric material is cut produces three main operational modes: transverse, longitudinal and shear.

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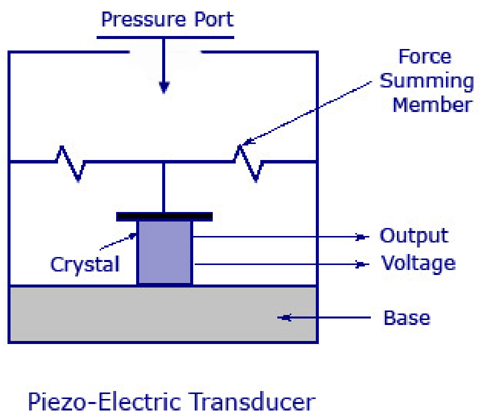


Figure 1 Piezoelectric Transducer (Hyan et al., 2013)

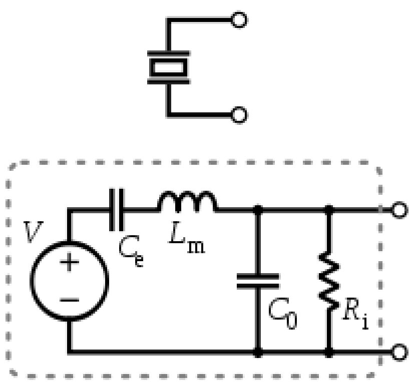


Figure 1a Schematic symbol and electronic model of a piezoelectric sensor (Zarnik et al., 2009)

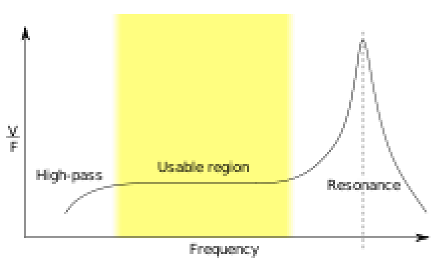


Figure 2 Frequency response of a piezoelectric sensor; output voltage vs applied force (Zarnik et al., 2009)

Transverse effect: A force applied along a neutral axis (y) displaces charges along the (x) direction, perpendicular to the line of force. The amount of charge depends on the geometrical dimensions of the respective piezoelectric element.

Longitudinal effect: The amount of charge displaced is strictly proportional to the applied force and independent of the piezoelectric element size and shape. Putting several elements mechanically in series and electrically in parallel is the only way to increase the charge output. The resulting charge is where is the piezoelectric coefficient for a charge in x-direction released by forces applied along x-direction.

Shear effect: The charges produced are strictly proportional to the applied forces and independent of the element size and shape. For elements mechanically in series and electrically in parallel the charge is in contrast to the longitudinal and shear effects, the transverse effect make it possible to fine-tune sensitivity on the applied force and element dimension.

A piezoelectric transducer has very high DC output impedance and can be modelled as a proportional voltage source and filter network. The voltage V at the source is directly proportional to the applied force, pressure, or strain. The output signal is then related to this mechanical force as if it had passed through the equivalent circuit.

A detailed model includes the effects of the sensor's mechanical construction and other non-idealities. The inductance L_m is due to the seismic mass and inertia of the sensor itself. C_e is inversely proportional to the mechanical elasticity of the sensor. C_0 represents the static capacitance of the transducer, resulting from an inertial mass of infinite size. R_i is the insulation leakage resistance of the transducer element. If the sensor is connected to a load resistance, this also acts in parallel with the insulation resistance, both increasing the high-pass cut-off frequency.

In the flat region, the sensor can be modelled as a voltage source in series with the sensor's capacitance or a charge source in parallel with the capacitance.

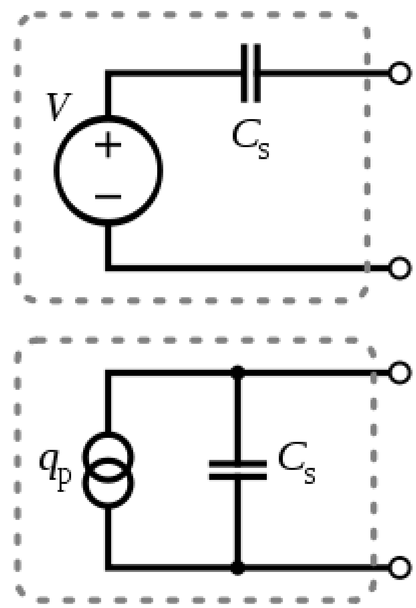


Figure 3 Sensor circuit (Zarnik et al., 2009)

Figure 4 Metal Disks with Piezo Material, Used in Buzzers or as Contact Microphones (Zarnik et al., 2009)

Sensor design

Based on piezoelectric technology various physical quantities can be measured; the most common are pressure and acceleration. For pressure sensors, a thin membrane and a massive base is used, ensuring that an applied pressure specifically loads the elements in one direction ((Zarnik et al., 2009., Ukpaka et al., 2005). For accelerometers, a seismic mass is attached to the crystal elements. When the accelerometer experiences a motion, the invariant seismic mass loads the elements according to Newton's second law of motion. The main difference in working principle between these two cases is the way they apply forces to the sensing elements. In a pressure sensor, a thin membrane transfers the force to the elements, while in accelerometers an attached seismic mass applies the forces.

Sensors often tend to be sensitive to more than one physical quantity. Pressure sensors show false signal when they are exposed to vibrations. Sophisticated pressure sensors therefore use acceleration compensation elements in addition to the pressure sensing elements. By carefully matching those elements, the acceleration signal (released from the compensation element) is subtracted from the combined signal of pressure and acceleration to derive the true pressure information (Zarnik et al., 2009, Ukpaka et al., 2005a). Vibration sensors can also harvest otherwise wasted energy from mechanical vibrations. This is accomplished by using piezoelectric materials to convert mechanical strain into usable electrical energy.

Advantages of piezoelectric transducers include the following: the piezoelectric transducer is available in desired shape, it has rugged construction, it is small in size, it has good frequency response, it has negligible phase shift, high output with negligible phase shift and self-generating, therefore no need of external source. Disadvantages of the piezoelectric in the following: piezoelectric transducer need high impedance cable for electrical interface because the device operates with the small electric charge, it is not suitable for measurement in the static condition, this Transducer output is low so some external circuit is attached to it, its output is affected by temperature variation, its output is affected if relative humidity rises above 85% or falls below 35% hence it has to be coated with wax or polymer material, it is very difficult to give desired shape to this material and also desired strength and output is low so some external circuit is attached to it.

Application of the Piezoelectric Transducers

Piezoelectric materials found many applications for industrial, environmental, medical, musical and personal use. These include: the piezoelectric transducers are more useful for the dynamic measurements, i.e. the parameters that are changing at the fast rate (Ukpaka et al., 2005b., Ukpaka, 2009). This is because the potential developed under the static conditions is not held by the instrument. Thus piezoelectric crystals are primarily used measurement of quantities like surface roughness, and also in accelerometers and vibration pickups. For the same reasons they can be used for studying high speed phenomenon like explosions and blast waves. They are also used in aerodynamic shock tube work and seismograph (used for measurement of acceleration and vibration in rockets). Many times the piezo sensors or transducers are used along with the strain gauges for measurement of force, stress, vibrations, etc.The automotive companies used piezoelectric transducers to detect detonations in the engine blocks. Piezoelectric transducers are used in medical treatment, so no chemistry and industrial processing equipments for monitoring the power (Zarnik et al., 2009). The most common application is in microphones where sound pressure is converted into an electric signal and this electric signal is amplified to produce a louder sound. It is normally used as an accelerometer due to its excellent frequency response. Automobile seat belts lock in response to a rapid deceleration is also done by the piezoelectric material (Ukpaka et al., 2005b).It is used to measure force, pressure and displacement in terms of voltage. It is used in Inkjet printers, buzzers, piezoelectric humidifiers and electronic toothbrushes. It is used in medical diagnostics. One of the applications of piezoelectric material is in electric lighter which is used in kitchens. When pressure is applied to the piezoelectric transducer, it generates an electric signal which causes flash to fire up. It is used is automatically open/close doors that you might have seen in Hotels, airports,

Some of the limitations of piezoelectric transducers are: Output is low: The output obtained from the piezoelectric transducers is low, so external electronic circuit has to be connected. High impedance: The piezoelectric crystals have high impedance so they have to be connected to the amplifier and the auxiliary circuit, which have the potential to cause errors in measurement (Ogoni and Ukpaka, 2004.,Ukpaka, 2009). To reduce these errors amplifiers high input impedance and long cables should be used. Forming into shape: It is very difficult to give the desired shape to the crystals with sufficient strength. Examples of piezoelectric material are: Barium Titanate, Lead zirconatetitanate (PZT) and Rochelle salt.

MATERIALS AND METHODS

A detailed introduction of the piezoelectric materials has been presented in the previous sections to provide a solid background of the topic.This research paper focuses on theuse of models to describe the behaviour of a piezoelectric crystal transducer in a pipeline system.Over time, the need for efficient control systems in flow stations across the globe has prompted assiduous research on this area inorder to obtain better ways of achieving optimum process flow systems and to reduce or exonerate from every avoidable industrial loss, accident, hazard or catastrophe.

In this work, the response art of the transducer during fluid flow is of high essence as it shows the relationship between parameters in the entire integrated system. A simple pressure transducer is made of a crystal, force summing chamber, base, voltage and a pressure port.

The next section elaborates more on the behaviour of the transducer during fluid flow as the simulation gives a concrete proof of the discussion above.

Mathematical Model Formulation

The model was developed based on the description stated below.
Using water in a pipeline as a case study the modelling is as follows:
Electric charge per time α pressure.

$$^{dO}/_{dt}\ \alpha\ CP$$

$$^{dO}/_{dt} = CP \qquad (1)$$

where, C = constant of proportionality during the process, P = pressure of flow

dQ/dt = electric charge accumulation in the transducer per time of flow
From the right hand side of the equation:

$$Recall\ Pressure = Force/Area$$

i.e. $P = F/A$ P (2)

$F = mass\ x\ acceleration\ (ma)$

So that $P = {}^{ma}/_{A,}$ but $a = \left[{}^{du}/_{dt}\right]$

Where${}^{du}/_{dt}$= rate of change of velocity per time.

$P = {}^{m}/_{A} \cdot \left[{}^{du}/_{dt}\right]$ (3)

Let${}^{m}/_{A} = k$

$Pdt = kdu$ (3a)

Integrating both sides of (3a) we have;

$P_o \int tdt = k_{uo} \int udu$

$Pt = k[u - u_o]$

Where u = final velocity; u_0 = initial velocity

$P = k[u - u_o]/t$P = k[u – u_0]/t (3b)

Recall $m = pv$from (3), we have;

$m = {}^{pv}/_{A}\ [{}^{du}/_{dt}]$

Where$v = A1$

Length (l) is used instead of height (h) because we are considering a linear pipe and not a perpendicular one.

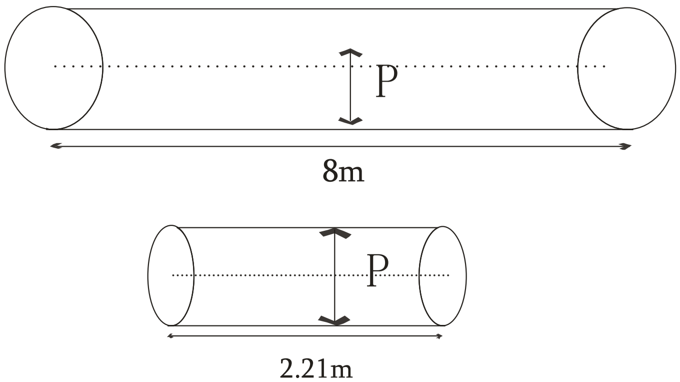
$P = {}^{pA1}/_{A}\ [{}^{du}/_{dt}]$

$P = p1\ [{}^{du}/_{dt}]$

So that:

$p = {}^{Pdt}/_{1du}$

So the influence of density during a fluid flow per length of the pipe increases with a decrease in the length of the pipe.



The diagram and simulation below explains the behaviour of density with the variation in length of a pipe.

Substituting (3) into (1) we have:

${}^{dO}/_{dt} = {}^{Cm}/_{A}\ [{}^{du}/_{dt}$dQ/dt (4)

Recall${}^{m}/_{A} = k$

${}^{dO}/_{dt} = Ck.[{}^{du}/_{dt}]$

so that; $dO = {}^{Ck}/_{du}$ (4a)

integrating both sides of (4a), we have;

$\int_O^Q dQ = Ck. \int_{uo}^{u} du$

$Q = Ck.[u - u_o]$ (5)

Therefore, electric charge accumulation in the transducer due to pressure exerted by the fluid in motion:
$Q = Ck.[u - u_o]$

Where, Q = charge accumulated in the transducer due to fluid movement, U = final velocity
U_0 = initial velocity
Resolving the LHS of equation (5), we have
$Q = It$
But: $I = {}^{E}/_{R}$

Where I is the current in the transducer capable enough to bring about a deflection on the scale as the charge per time is transformed to it through the aid of an amplifier.

So that:$Q = {}^{Et}/_{R}$ (6)

Where,E = voltage in the transducer, R = resistance

Substituting (6) into (5), we have:

${}^{Et}/_{R} = Ck.[u - u_o]$

$E = {}^{RCk}/_{t}\,[u - u_o]$ (7)

Differentiating both sides of equation (7), we have

$dE = {}^{RCk}/_{t}\,.du$ dE = RCk/t. du (8)

integrating both sides of equation (8), we have:

$\int_{v1}^{v2} dE = {}^{RCk}/_{t} \int_{o}^{u} du$

$[E_2 - E_1] = RCk{}^{u}/_{t}$ (9)

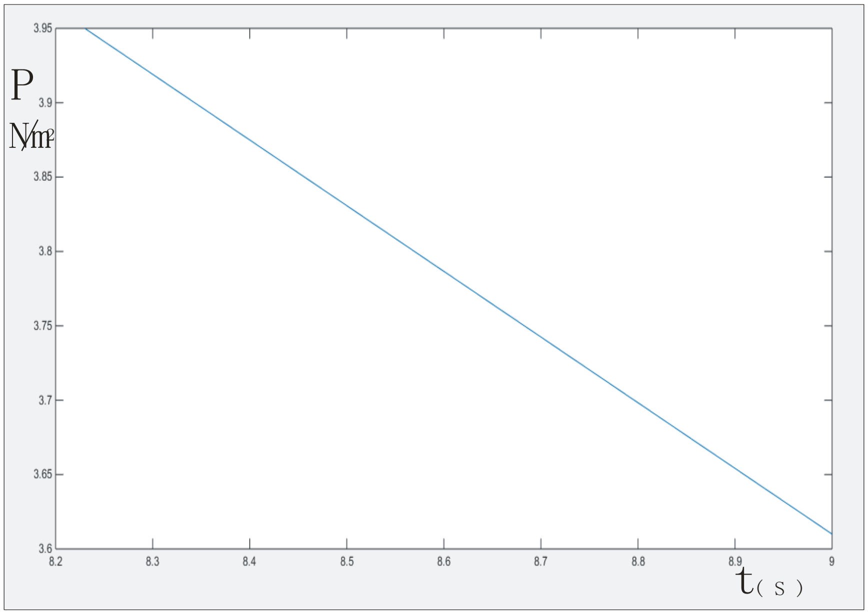


Figure 5 Graph of Pressure against Time

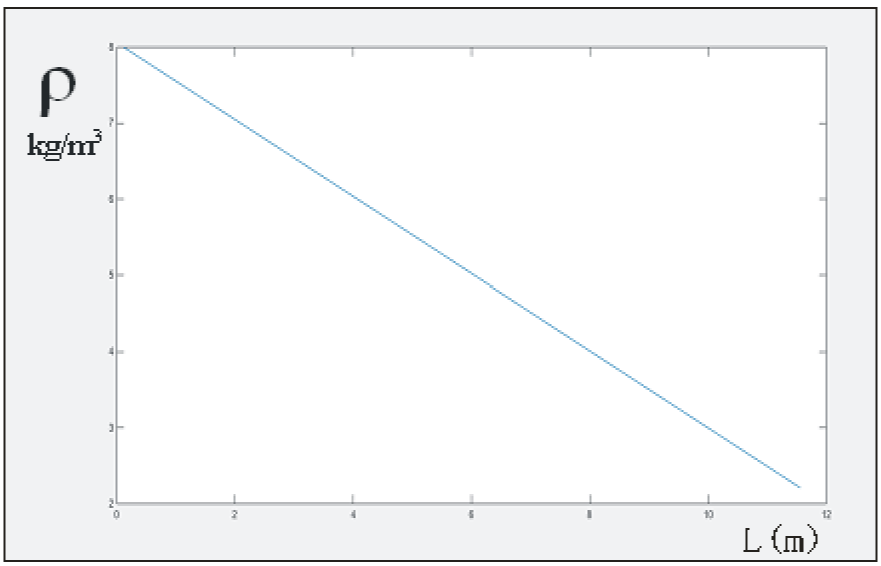


Figure 6 Graph of Density against Length

Computational Procedure

The following approach was used in the computational of the above developed mathematical model

$P = k\ [u - u_o]/t$(3b)

Taking k = 10kg/m^2 and the initial and final velocities to be 0.75m/s and 4m/s respectively; t = 8.23s

P = 10[4 – 0.75]/8.23

P = 3.95N/m^2

Assuming time of flow is increased to 9s, we have

P = 10[4 -0.75]/9

P = 3.61 N/m^2

For density

The mathematical expression for density is as stated

$p = {}^{Pdt}/_{1du}$

The influence of density on a fluid pipeline:

take u_0 = 0.75m/s, u = 4m/s, P = 3.95N/m^2, l = 8m, t = 8.23, t_0 = 9

ρ = 3.95(9 - 8.23)/8(4 – 0.75)

ρ = 0.117kg/m^3

but if the length is shortened by 5.79m; the density impart would be:

ρ = 3.95(9 – 8.23)/2.21(4 – 0.75)

ρ = 11.56kg/m^3

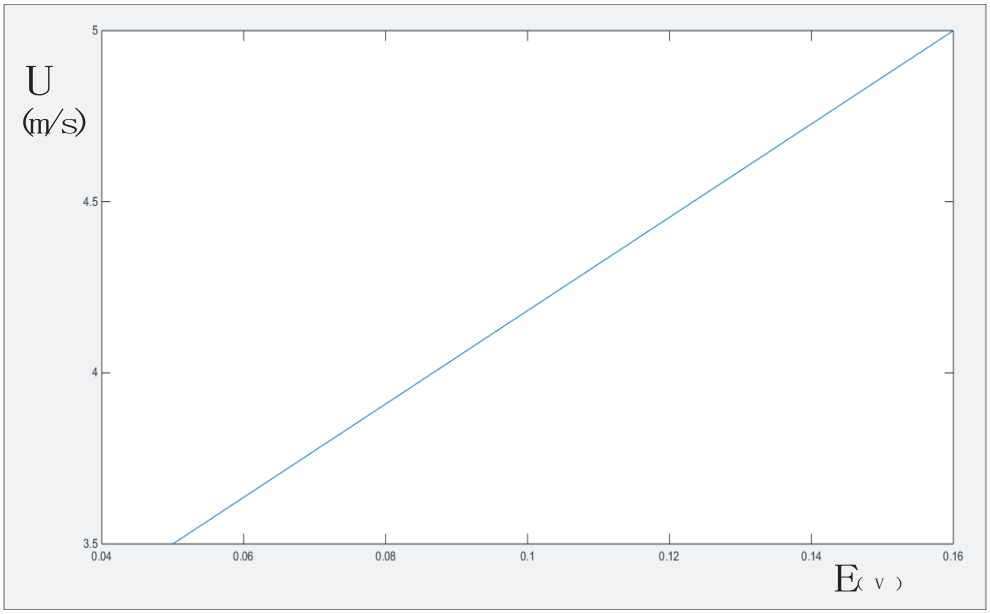


Figure 7 Graph of Velocity against Voltage

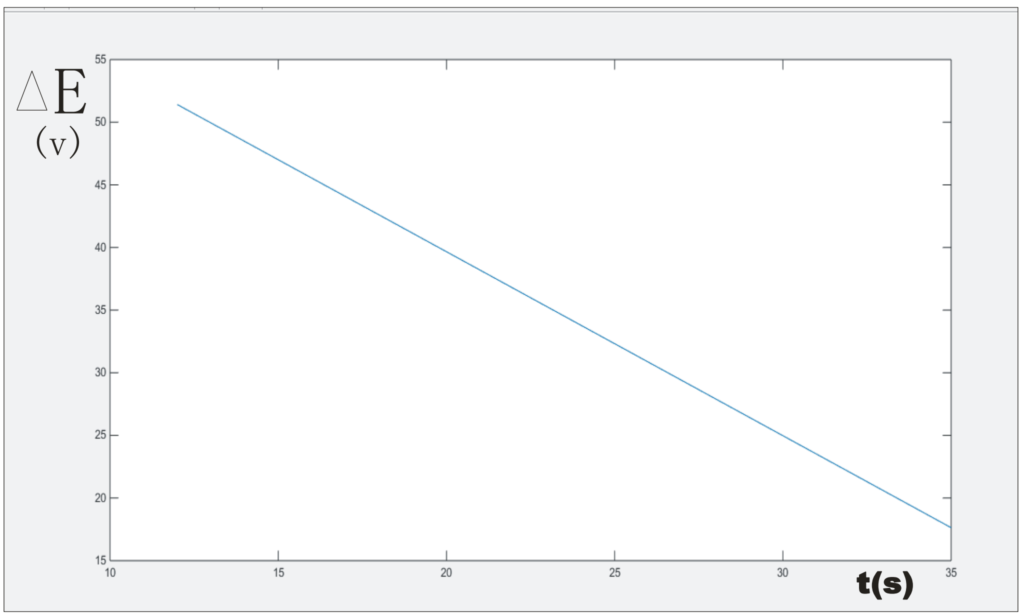


Figure 8 Graph of Voltage against Time

For velocity

$[E_2 - E_1] = RCk^{u}/_{t}$ (10)

At voltages of E_2 = 5V, E_1 = 2.8V; what would be the response of velocity of flow within the system.

Take R = 23.5Ω, k = 7kg/m^2, C = 0.75, t = 9s

We have:
[5 – 2.8] = 23.5 x 0.75 x 7 x U/9
U = 2.2/13.71
U = 0.16m/s
When the maximum voltage in the transducer is decreased to 3.5V, we have:

(3.5 – 2.8) = 23.5 x 0.75 x 7 x U/9
U = 0.7/13.71
U = 0.05m/s

Therefore, an increase in the velocity of fluid flow leads to a corresponding increase in the voltage of the transducer and vice versa.

For voltage

If time is varied between 12s and 35s respectively, voltage in the transducer at each interval would be: take u = 5m/s
At first interval:
$E_2 - E_1 = RCk^{u}/_{t}$
ΔE = 23.5 x 0.75 x 7 x 5/12
ΔE = 51.41volts

At second interval
$\Delta E = 23.5 \times 0.75 \times 7 \times 5/35$
$\Delta E = 17.63$volts

RESULTS AND DISCUSSION

Therefore, as time increases pressure decreases in a flow system and vice versa, below is the graph of Pressure against time: The result presented in Figure 5 illustrates the relationship between pressure and time. Decrease in pressure was observed with increase in time in the pipe flow system, the variation in time as well as increase in pipe flow length of the system. The characteristics of the system pressure upon the influence of time were monitored, predicted and simulated using Matlab computer language program as shown in figure 5. Figure 6 demonstrate the relationship between the density and pipe flow length. It is seen that the density value increases with increase in pipe flow length. The variation in the fluid density can be attributed to the variation in the flow length of the pipe as well as the internal friction created during the fluid flow in the system. From figure 7 it is seen that increase in velocity resulted to increase in voltage of the system. The variation in the velocity can be attributed to variation in voltage of the system. The figure 7 illustrate the relationship between velocity and voltage in a piezoelectric crystal process of fluid flow in a pipe system. Figure 8 illustrate the relationship between voltage and time. Result figure 8 demonstrates decease in voltage with increase in time. The variation in the voltage can be attributed to the variation in time.

CONCLUSION

The development of this model describes how better to utilize a fluid flow system in a pipeline to achieve optimal operation. Further, companies that use pipeline systems for transportation of their products or raw materials should invest in piezoelectric pressure transducers to reduce hazard incidents, optimal productivity and cost of maintenance.

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